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Three-phase induction generators for single-phase power generation: An overview

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ABSTRACT

The usage of three-phase induction generators for energy production in non-conventional energy systems covers a dynamic research area. When single-phase consumers are predominant, besides the use of a single-phase generator, a three-phase induction machine with a proper balancing circuit represents a reliable alternative.

Over the last 25 years, efforts have been made to enhance the balanced operation of a three-phase induction generator in single-phase mode. This paper presents a survey of the existing literature, focusing on several significant aspects such as phase balancing methods, excitation requirements, steady-state and dynamic analysis, and maximum available power in single-phase mode of operation.

Contents

1. Introduction

Nowadays, renewable energy sources such as wind, solar and micro-hydro are increasingly being used for electric energy generation [1]. This aspect is determined on one hand by the depletion and environmental impact of conventional energy sources and on the other hand by the need to ensure clean energy for consumers located far from the distribution networks. In the case of low power micro-hydro plants an induction machine is mainly employed as generator. The literature concerning the autonomous operation of induction generators is very vast; a well documented survey can be of real help for researchers working in this field [2].

In many cases, isolated consumers require single-phase power; thus, the single-phase induction machine appears as a reliable alternative in supplying such consumers. A reasonable number of research articles can be found within this area of interest [3,4]. One of the main issues related to this generator is the choice of the capacitor(s) used to excite the machine. Different configurations have been presented in [5]: the simplest one relies on one capacitor across the auxiliary winding; another one has in addition

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one variable capacitor across the main winding, while the third one is completed with one more capacitor in series and a variable one in parallel with the main winding. The amount of required capacitance for excitation has been computed for shunt and series capacitors [6]. The steady state regime for shunt, short-shunt and long-shunt configurations has been analyzed in [7,8]; for the same regime the analysis has been done based on the harmonic balance technique [9] and on a model using graph theory and fuzzy logic [10]. The authors in [11] proposed the Newton–Raphson method to solve the nonlinear equations which resulted from the machine equivalent circuit. The method developed in [12] employed the symmetrical components analysis to obtain the equivalent circuit, while in [13] the effect of rotational direction is analyzed. Simulations have focused on the self-excitation process and voltage collapse [14] and on the behavior of a grid-connected generator during grid faults [15]. The stable operation in autonomous mode is ensured either by a single-phase ELC [16], by a single-phase PWM inverter supplied from batteries [17,18] or by a static VAR compensator based on thyristors [19].

However, the single-phase induction machine has a series of drawbacks with respect to a similar three-phase machine of the same power (it is more expensive, has lower efficiency and consequently a worse power per weight ratio); for series production, its power is limited to 3–4 kW. In the meantime, three-phase induction motors are available in a wide power range and models. Thus, efforts have been made to allow the operation of a three-phase induction generator in single-phase mode. This paper presents an overview of the existing literature in this field of interest. The paper is organized as follows: Section 2 presents the main phase balancing methods, while in Section 3 the excitation requirement for single-phase operation is analyzed. The steady-state and dynamic analysis for this particular operating regime is presented in Section 4 and the performance evaluation and maximum available power in single-phase mode are addressed in Section 5.

2. Phase balancing methods

The main characteristic of a three-phase induction generator supplying single-phase consumers is the unbalanced regime which cannot be allowed for stable operation. Either it operates in autonomous mode, or connected to a single-phase network, the generator requires phase balancing. Thus, the case in which the generator supplies three-phase balanced loads is replicated.

A brief chronological analysis shows that one of the early balancing methods focused on the three-phase induction generator operation on a single-phase grid. Ref. [20], one of the first articles in this field, proposes no less than four distinctive balancing configurations, three for star and one for delta connected induction generators. The balancing is done using passive circuit elements and employs either two capacitors, two capacitors and a unity turns ration transformer, three capacitors and a transformer, or, in the last case, two capacitors (connected in series and parallel). Another early solution introduced two shunt reactances, equal in magnitude, one being a purely inductive, while the other a purely capacitive element [21]. In parallel, the autonomous operation has been investigated as small generation units based on renewable energy sources (especially micro-hydro) have been requested to deliver single-phase power to isolated consumers. For instance, Ref. [22] was the first to introduce the "C–2C" term as balancing method for a delta connected generator, while Ref. [23] proposed the use of only one capacitor for self-excitation, for both star and delta connections.

From another perspective, the phase balancing topologies, generally named as "phase converters", can be divided into two major categories: based on passive circuit elements [24–57] (excitation capacitors, impedances) or on power electronic converters [58–67]. For the first balancing method the resulting configuration (and the number of requested capacitors) is imposed by the generator internal connection (star or delta); this aspect will be detailed in the paragraphs below. For each topology, a schematic representation is provided through Figs. 1–11.

2.1. Passive circuit elements

For star connected generators, the balancing topologies rely on:

- three capacitors, from which two of the same value, in the form of the Fukami connection [24–35] (Fig.1);
- three excitation capacitors in the form of the Smith connection and the re-arrangement of the stator winding [36–38] (Fig. 2);
- one capacitor, connected across one of the three phases, while the load is connected across the first phase; thus three configurations are possible [39,40] (see Fig. 3a); and
- one capacitor, connected either between two phases or across one phase, while the load is connected across two phases (see Fig. 3b); [41].

For delta connected generators, the balancing topologies rely on:

- one capacitor, connected in parallel with the load (this configuration is also called *single-phase mode of operation*—SPMO)

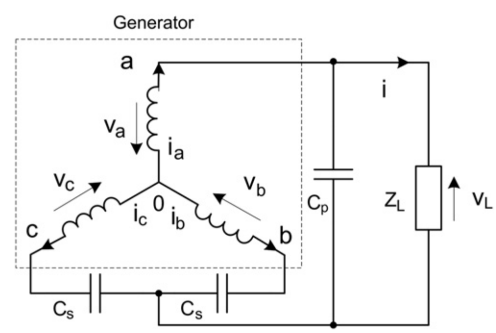

Fig. 1. The Fukami connection [24–35].

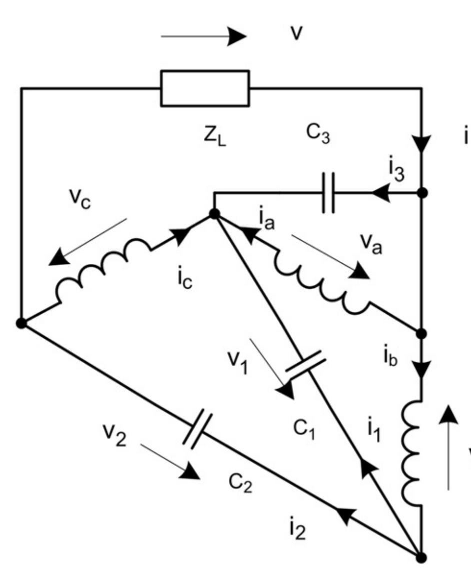

Fig. 2. The Smith connection [36–38].

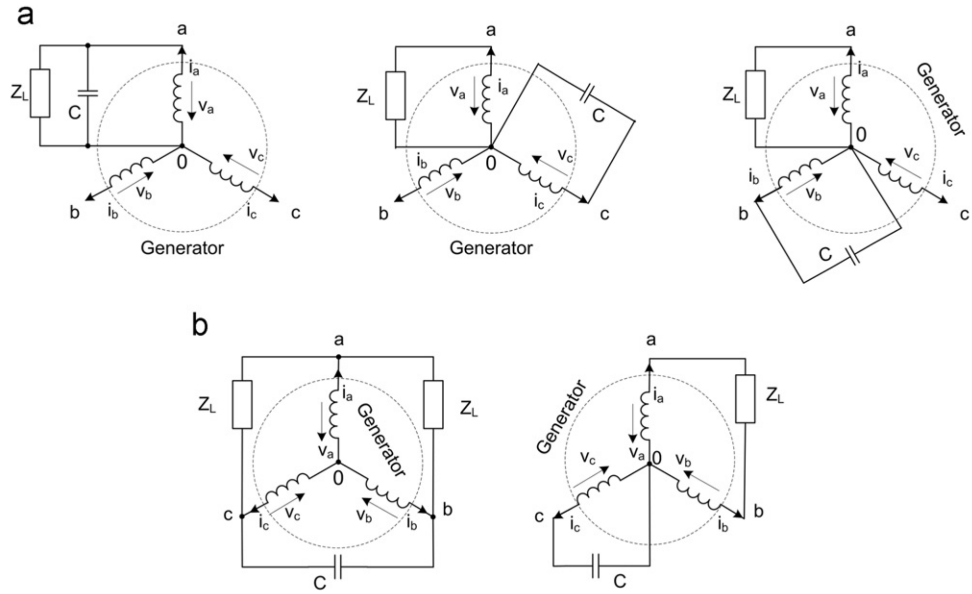

Fig. 3. Star connected generator with one capacitor [39–41]. (a) The load connected across one phase and (b) The load connected between two phases.

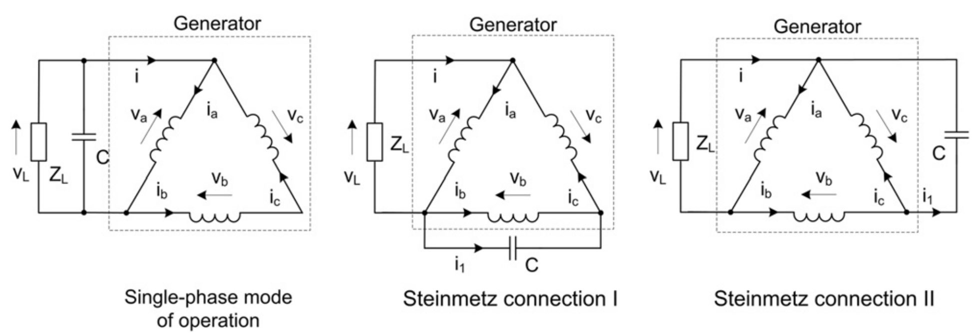

Fig. 4. Delta connected generator with one capacitor [42–45]..

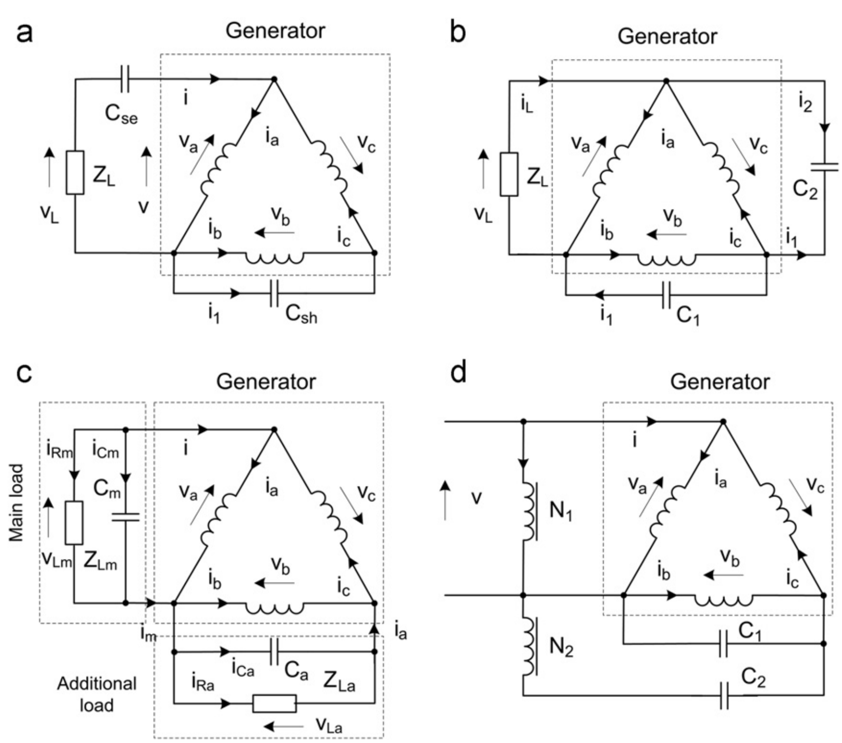

Fig. 5. Delta connected generator with two capacitors [46–51]. (a) Shunt and series capacitaor excitation; (b) Two shut excitation capacitors; (c) Modified Steinmenz connection and (d) Current injection transformer.

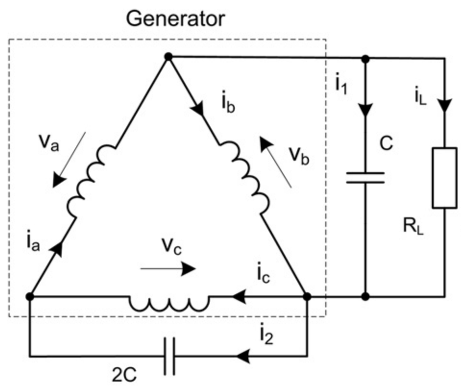

Fig. 6. The C–2C connection [52–57].

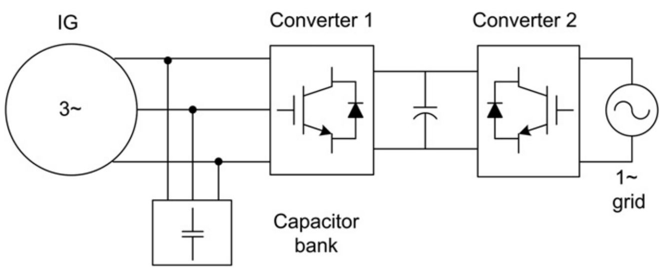

Fig. 7. The Back-to-back topology [58–61].

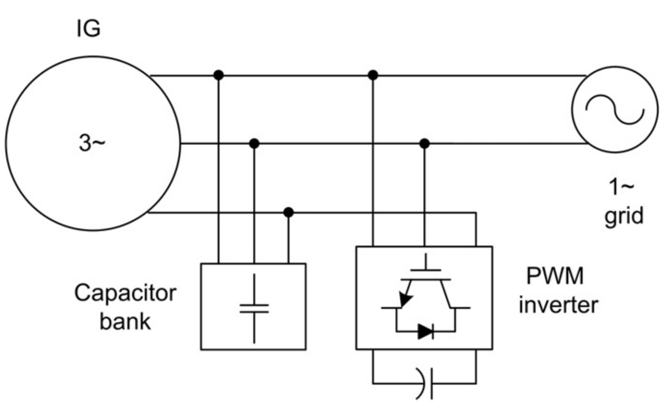

Fig. 8. The PWM inverter based topology [63].

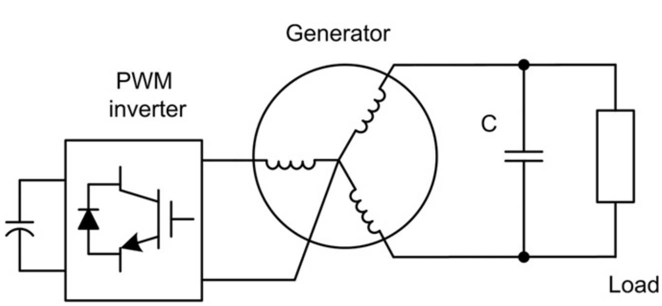

Fig. 9. The TSCAOI topology [64,65].

or in the form of Steinmetz connections I and II [42–45] (Fig. 4);

- two capacitors: one connected across the lagging phase and the other in series with the load, across the reference phase [46,47] (Fig. 5a);
- two capacitors and the load connected each across one phase [48] (Fig. 5b);

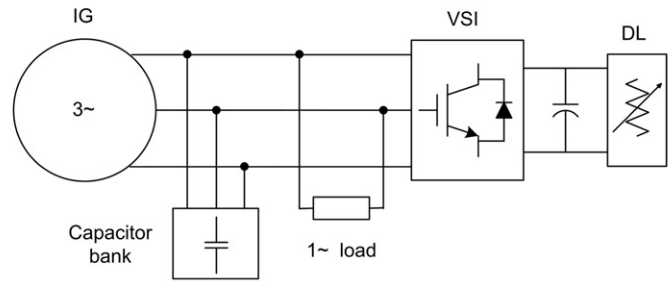

Fig. 10. The VSI-DL topology [66,67].

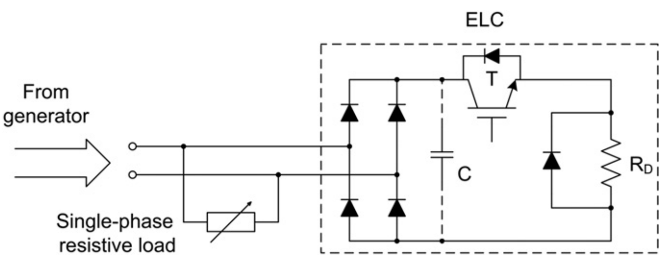

Fig. 11. The ELC structure [35,54–56].

- two capacitors under the form of the modified Steinmetz connection [49,50] (Fig. 5c);
- two capacitors and a current injection transformer [51] (Fig. 5d); and
- C–2C connection: 2C capacitance across one phase and one C across another phase and in parallel with the load [52–57] (Fig. 6).

2.2. Power electronics converters

In case the machine is connected to a single-phase power network, there is the possibility of making the interconnection and phase balancing by using two power bridges in back-to-back configuration (Fig. 7). By passing through direct current the phase problem is solved [58–61]; the same topology is applied when a local load (i.e. single-phase induction motor) is supplied [62]. Ref. [63] reports that the use of a single PWM inverter enables balanced operation for the generator when connected to a single-phase feeder (Fig. 8).

Another possible configuration is the one in which a single-phase power bridge is connected across one phase and balances the generator active (and reactive if necessary) power circulation while the load is connected between the remaining two phases [64,65] (Fig. 9); this topology is also known as two-series-connected-and-one-isolated (TSCAOI). A combination between a three phase voltage source inverter (VSI) and a dump load (DL), operating in parallel with a delta connected generator, enables balanced currents through the machine when supplying single-phase loads [66,67] (Fig. 10).

When power electronics based converters are used, some might act as balancers for the three-phase machine. For instance, a simple configuration relies on a delta connected machine with the C–2C connection, having in parallel with the main (resistive) load a circuit named Electronic Load Controller (ELC) that dissipates the exceeding active power [54–56]. Thus, the ELC participates at phase balancing by maintaining a constant load at the generator leads. The same configuration is encountered also for star connected machines with the Fukami connection [35]. The ELC structure, applicable for both star and delta connection is depicted in Fig. 11. It contains a single-phase diode bridge,

sometimes a filtering capacitor, a transistor playing the role of a chopper and a dissipative resistor.

2.3. Latest balancing methods

The latest methods/topologies of single-phase power generation using a three-phase induction generator rely on power electronics circuits with adequate control. The above-mentioned TSCAOI topology uses the single-phase bridge and a DC source to balance the active power circulation in case of varying loads/rotor speeds; furthermore, the bridge provides the generator excitation current. An additional chopper and resistor on the bridge DC side facilitate the exceeding active power consumption. The control loop is based on a single PI controller and has as input value the voltage across the load. A partially similar topology especially designed to charge batteries has been developed in [68]. It consists in a single-phase controlled semi-converter (rectifier) connected to the batteries through a smoothing inductor, the IG being excited by a three-phase capacitor bank. Three control strategies are applied for the single-phase bridge: Phase Angle Control (PAC), Symmetrical Angle Control (SAC) and Extinction Angle Control (EAC). Another configuration, mentioned in Section 2.2 is based on the VSI+DL topology. By operating at constant synchronous frequency the voltage source inverter imposes the IG frequency while the dump load maintains the system voltage constant by dissipating the exceeding active power. The VSI control loop contains an unbalances compensation block based on two proportional-resonant (PR) controllers. Its role is to redistribute the currents through the VSI in order to balance the IG currents.

3. Excitation requirements; calculation methods

There are several ways of providing the amount of necessary excitation for a three-phase induction generator feeding single-phase loads. One, two or three capacitors can be used; for each situation, the final arrangement will include also the load and will be influenced by the generator internal connection (star or delta).

When phase balancing is achieved with the help of power-electronics based converters, the required capacitance is computed as for a balanced three-phase generator and three capacitors in star or delta connection are required [58–60,66–69]. Moreover, in [69], the authors suggest that two banks of three-phase capacitors can be used, one unit for single-phase loading and the other to be put in parallel for three-phase loading. For instance, in [36], for a given load impedance and per-unit speed, a nine-step iterative procedure is used.

In case of the C–2C balancing method [55], a complex iteration is employed: starting from Kirchoff's Laws, using symmetrical components theory and finally minimizing the obtained function with the help of the sequential unconstrained minimization technique the required capacitance is computed. In [57], a very general method for the same capacitor arrangements is given. The C value is determined by imposing the condition that the load current should be equal with the C capacitor current multiplied by $\sqrt{3}$.

In the case of a delta-connected generator excited with two capacitors placed over two phases and the load across the third one, the capacitors role is, besides ensuring minimum self-excitation, also to minimize the unbalances between the stator currents [48]. In order to determine its value, a function containing both the generator equivalent impedance and unbalance factor is minimized with the help of a sequential numerical optimizer, which combines a standard genetic algorithm and a classical constrained solver.

The Steinmetz connection requires the use of a single capacitor to magnetize the generator. The minimum capacitance required to initiate voltage build-up can be calculated starting from the generator input impedance and self-excitation conditions [70]. By solving the two resulting nonlinear equations the excitation frequency and the minimum excitation capacitance are obtained. Furthermore, the required capacitance for constant voltage operation when the generator is loaded can also be found.

For a star connected machine, excitation can be done with one capacitor connected across one phase (phase excitation) or between two phases (line excitation) [41]. Phase and line excitations complement one another, but line excitation is desirable. When phase balancing is achieved using the Fukami connection, three capacitors are required. An algorithm was developed in [26,31] to determine the required capacitance for maximum power output in case the generator is feeding inductive and capacitive loads. The algorithm is structured in a 12 steps flowchart.

Other researchers use eigenvalue methods to determine both minimum and maximum capacitance values [28,44]. By choosing a small/large initial value the minimum/maximum excitation capacitance can be computed in 2–4 iterations. The method has the advantage of avoiding the solving of high order nonlinear polynomial based on a per phase equivalent circuit model.

The same technique of eigenvalue and eigenvalue sensitivity is used in [29,39]. For three configurations of a delta connected generator that employ only one excitation capacitor (i.e. single-phase mode of operation, Steinmetz connections I and II), both minimum and maximum values are determined in case of no-load and resistive load operation [29]. In terms of minimum and maximum capacitance, the Steinmetz connections I and II are identical when the loading resistance and rotor speed of the studied SEIG are the same. The other connection requires a larger value for the minimum capacitance under both no-load and loading conditions and larger/smaller values for maximum capacitance under no-load/loading conditions with respect to the other two connections. The same approach is developed in [39], this time for a star connected generator.

4. Steady-state and dynamic analysis

Several models have been developed to analyze the steady-state and transient performance of a three-phase induction generator supplying single-phase loads. The modeling allows the maximum/minimum capacitance calculation, operating parameters determination and the conditions for phase balancing. Symmetrical components analysis is widely used [24,28,30,33,42,50–52,54].

A time domain mathematical model that includes the electromagnetic unbalances inside the machine is given in [71,72]. It is used because the frequency domain modeling does not allow such analysis; they lead to torque swings due to unbalanced currents and hence unbalanced magneto-motive forces.

In [51], the conditions for phase balancing are deduced from the phasor diagram. The resulting capacitance for perfect phase balance depends on the generator admittance, power factor angle and turns-ratio of the transformer. The authors state that the phase balancing is achieved with the Steinmetz connection for a power factor angle of $2\pi/3$. The balancing condition from [73] is determined by imposing the negative-sequence voltage component to be equal to zero. Ref. [38] shows that the susceptances values for phase balancing depend on the generator positive-sequence impedance angle.

Usually, for parameters determination, the mathematical model is reduced to two unknown quantities (the magnetizing reactance Xm and the p.u. frequency f) [53]. Once they are found,

the air-gap voltage can be determined; the currents, terminal voltage and output power can also be computed.

In [34,46], the pattern search method of Hook and Jeeves is used to determine the machine parameters. A new parameter called compensation factor is introduced, which is actually the ratio between the parallel and series capacitance [46].

Mahato et al. [47] have used the sequential unconstrained minimization technique (SUMT) in conjunction with Rosenbrock's method of rotating coordinates for the steady-state analysis. Starting from a matrix equation relating the positive and negative sequence components of the stator currents and circuit impedances, a genetic algorithm (GA) is employed to determine the values of both generator frequency and magnetizing reactance for a given rotor speed and load [69].

In [23], modeling starts from two nonlinear equations with four unknowns, which are solved with the help of the Newton–Raphson method. Therefore, the values of the magnetizing reactance and frequency are found. A three steps procedure is employed to determine the relation between the air-gap voltage and the magnetizing reactance. Then, for both star and delta connected machines, the conditions for excitation under no-load/load are imposed and the performance characteristics are calculated.

Ref. [33] proposes a dynamic model for resistive and inductive loads, assuming capacitors of equal values while in [54] dynamic modeling is done with the help of differential equations, which are solved using the Runge–Kutta method. Shilpakar and Singh [52] have also investigated the dynamic behavior; the magnetizing inductance is found from a fourth-order polynomial function of the magnetizing current. The model also incorporates the magnetic circuit cross-saturation with the nonlinear differential equations of the dynamic model being solved via a numerical method.

Other papers emphasize the disadvantages of the symmetrical components analysis and propose new methods to determine the parameters [44,45]. In consequence, Ref. [45] relies on a time-stepping finite element analysis coupled with external circuit equations; it allows dynamic performance analysis, in the meantime avoiding the use of equivalent circuit parameters. Ref. [44] states that the major drawback of symmetrical components is that the dynamics of transient performance cannot be directly predicted and analyzed. Thus, the equations are written in matrix form and the dynamic equations are derived in advance.

In addition to [29], for dynamic analysis, two new terms are introduced: the voltage unbalanced factor K_{ubfv} and the current unbalanced factor K_{ubfi} [43]. The Steinmetz connection I has the largest unbalance factor (for both voltages and currents), the Steinmetz connection II has the lowest voltage unbalance, while the SPMO has the lowest current unbalance. Steady-state analysis shows that the loading has an influence on the unbalance factors. Therefore, the Steinmetz I has the lowest K_{ubfv}, SPMO has high values of K_{ubfv} for low loads and high values under high loads, while in the case of the Steinmetz II the things are mirrored. Wang and Cheng [40] proposed a comparative study between the conventional piecewise linear approximation and a curve fitting method that aims to determine the generator magnetization curve; the second one reports better experimental results.

5. Performance evaluation; maximum available power in single-phase mode

The goal of the balancing topologies is to minimize the unbalanced factor corresponding to the generator currents. The aspect of maximum power generation in single-phase mode should be treated in close relation to the degree of unbalance in terms of currents and voltages.

One of the main conclusions that results from the literature analysis is that balanced operation occurs only at (and sometimes around) a fixed load value. Ref. [74] analyzes both maximum power and unbalanced degree for different topologies (among which Fukami and C–2C). The unbalance factor (for both voltages and currents) is lower for the C–2C connection (with respect to Fukami connection); the maximum available power is also higher for this configuration (66.67% with respect to 60% from the generator nominal power).

For delta connected machines, Refs. [49,50] report around 1.9 kW from a 2.2 kW generator. Thus, the available power in single-phase mode is around 85%. When the C–2C connection is employed, experimental studies report an available power of 86% in single-phase mode [22,53], while Ref. [57] gives a value of 82%. For the same balancing method, a 7.5 kW machine fitted with a single-phase ELC delivers 3 kW [54,55], which is around 40% of the machine nominal power. Good transitory performance is obtained with the help of power electronics in Ref. [67], as single-phase loads are converted into equivalent three-phase ones and balance operation is ensured for varying loads. When the machine operates connected to a single-phase grid, its performance can be affected by the rotational direction. Ref. [75] concludes that, when the generator is driven in reverse direction, it behaves better in terms of phase imbalance, efficiency and power factor.

For star connected machines, Ref. [26] shows that a 2.2 kW generator supplies a 0.8 PF load; the maximum power is 44.5%; for a load with unity power factor (PF) load the value is 44.8%. The currents are balanced only for a fixed operating point and low loading and the available power is given for the situation in which the highest current (*s*) do not exceed the nominal value, but in this scenario they are highly unbalanced (1.2 with respect to 4.2 and 4.1A). The authors report a similar behavior in [33]. In addition to [26], Ref. [31] gives almost the same ratio of available power in single-phase mode for a 7.5 kW generator (i.e. 3.7 kW). For a 3.73 kW machine, the load and ELC are supplied with 1 kW of power [27]. The experiments made on a 200 V/2.2 kW machine reveal that in single-phase mode of operation the voltage is around 170 V while the load power is limited to 1.3 kW [24]. In case of a 2.2 kW machine, frequency varies with output power (between 49 and 50 Hz) [30]. As the load power increases, the output voltage increases a little (for inductive loads) and decreases (for unity-power factor loads); the currents become more unbalanced as the load increases. The total power supplied to the loads is around 85% of the power obtained with balanced excitation [41]; while Ref. [64] reports that approximately 2 kW can be obtained from a 3 kW machine, but only in case of a constant load.

6. Conclusions

The review of the literature concerning the operation of a three-phase induction generator supplying single-phase loads has yielded several significant conclusions:

- The main issue that should be addressed is the unbalanced regime, which cannot be allowed for stable operation. The phase balancing is accomplished by phase converters based on passive circuit elements only, on power electronics converters or on a combination between the two. The most encountered balancing topologies based on passive elements are the C–2C for delta and Fukami for star connected generators. In the case of power electronics, three/single phase controlled bridges are employed, while for the latter category the C–2C topology in

combination with a single-phase Electronic Load Controller is used.

- The number of capacitors used for self-excitation varies from one to three, for both machine internal connections (star or delta). The corresponding capacitance is determined through algorithms of different complexities; the simple ones are based on a single condition while others more complex rely on iterative procedures and minimization techniques. The minimum/maximum capacitance values for no-load/full-load operation are usually computed with the help of the eigenvalue/eigenvalue sensitivity techniques. When power converters are used for phase balancing the required capacitance is determined as for a balanced three-phase generator (excepting the TSCAOI topology).
- Symmetrical components are widely used for steady-state and dynamic analysis. For the determination of the parameters involved in excitation capacitors calculation, the mathematical model is usually reduced to two unknown quantities: the magnetizing reactance Xm and the p.u. frequency f. Once they are found, other parameters like the air-gap voltage, the currents, the terminal voltage and output power can also be determined. As alternatives to symmetrical components a time-stepping finite element analysis and a procedure for deriving the dynamic equations can be mentioned.
- Balanced operation is obtained only for fixed load values when using passive devices. This aspect can be improved with the help of power electronics, either by using the ELC in parallel with the main load, or by employing three/single phase controlled bridges. The maximum available power in single-phase mode of operation is treated in close relation with the degree of unbalance in terms of currents. The existing references report values between 40% and 86% from the corresponding power in three-phase mode.

Based on the continuous development of the power electronics domain, it is expected that better balancing and control methods will improve the operation of three-phase induction generators supplying various single-phase loads.

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